Accessing nuclear structure with high-energy nuclear collisions

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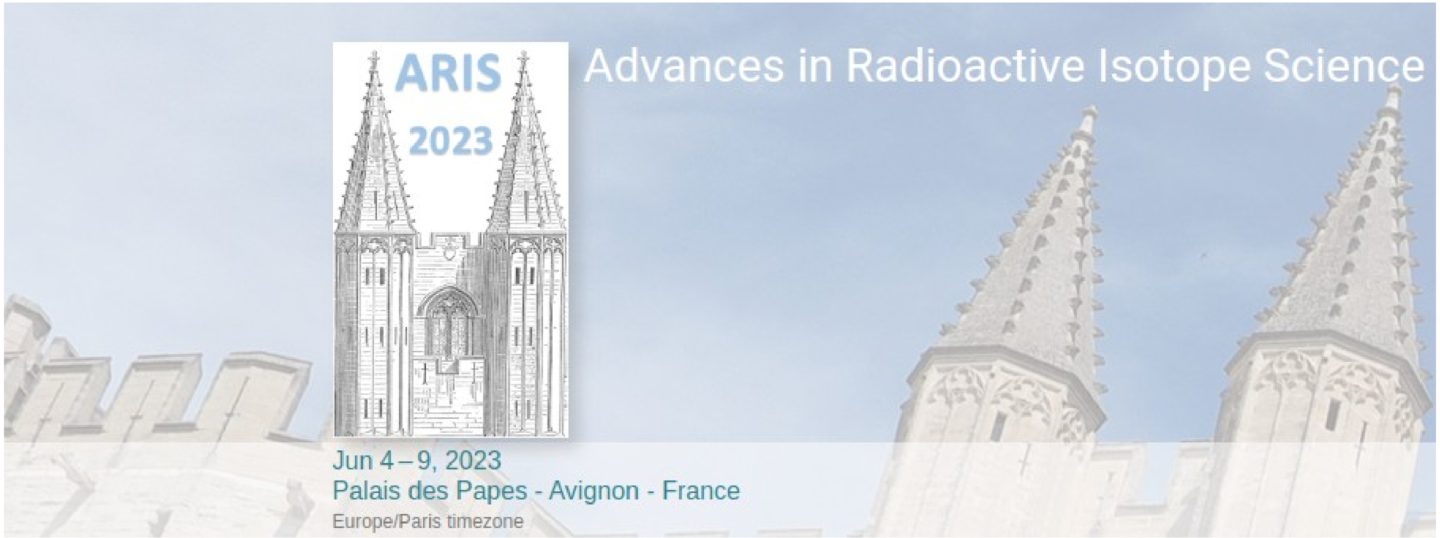


Much activity at the intersection of nuclear structure and high-energy nuclear collisions.

ExtreMe Matter Institute EMMI
EMMI Rapid Reaction Task Force
Nuclear Physics Confronts Relativistic Collisions of Isobars
Heidelberg University, Germany, May 30 – June 3 & October 12-14 2022

Organizers:
Giuliano Giacalone
Jiangyong Jia
Vittorio Somà
You Zhou

cea
ESNT
Espace de Structure Nucléaire Théorique
DSM - DAM

Deciphering nuclear phenomenology across energy scales
https://esnt.cea.fr/Phocea/Page/index.php?id=107 **Sep 20th - Sep 23rd 2022**

Organizers:
Giuliano Giacalone (ITP Heidelberg)
Jean-Yves Ollitrault (IPhT Saclay)
You Zhou (Niels Bohr Institute)

Intersection of nuclear structure and high-energy nuclear collisions

Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jacquelyn Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

- → Next Initial Stages conference (Copenhagen, 2023) will have a track related to nuclear structure.
- → Input to Nuclear Physics LRP in the US, both hot QCD (e.g. arXiv link) and nuclear theory.
- → Contributed input to NUPECC LRP 2024 [link with Y. Zhou (NBI Copenhagen), see slide 29]
- → Topical Issue on EPJA on the intersection of the two areas (link ~20 papers in 2023) [T. Duguet, G. Giacalone, V. Somà, Y. Zhou]

OUTLINE

1 – Nuclear collisions at high energy.

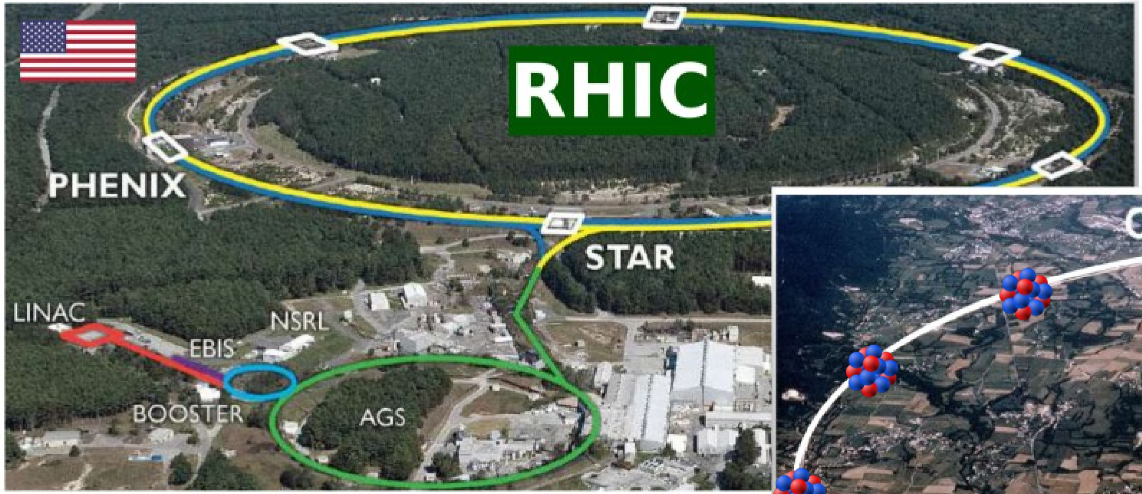
2 – Nuclear structure input.

3 – Milestones from the past two years.

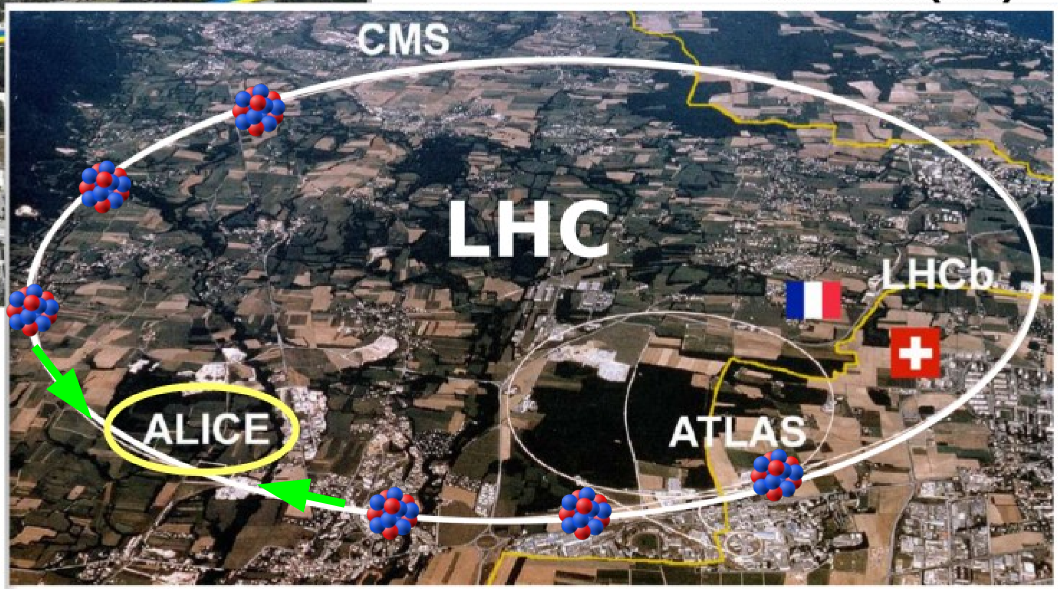
4 – Prospects.

1 – HIGH-ENERGY NUCLEAR COLLISIONS

Long Island (NY)

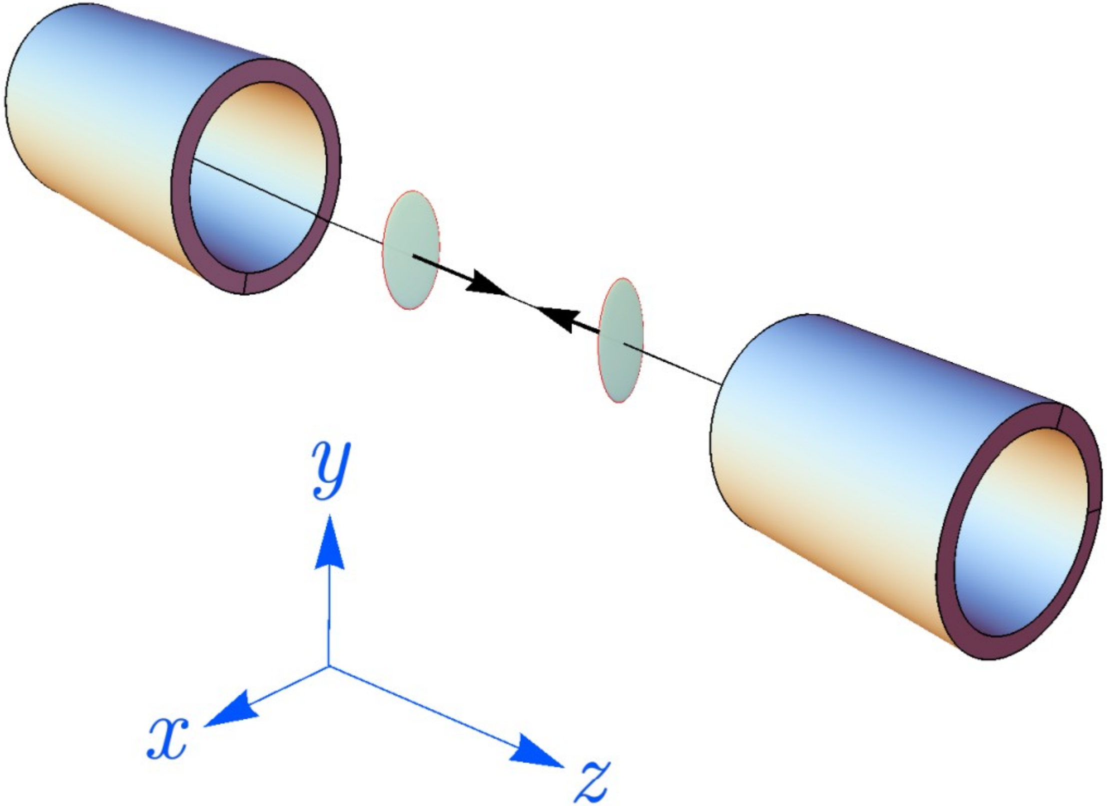


Geneva (CH)



Huge experimental program. The largest colliders in the world.

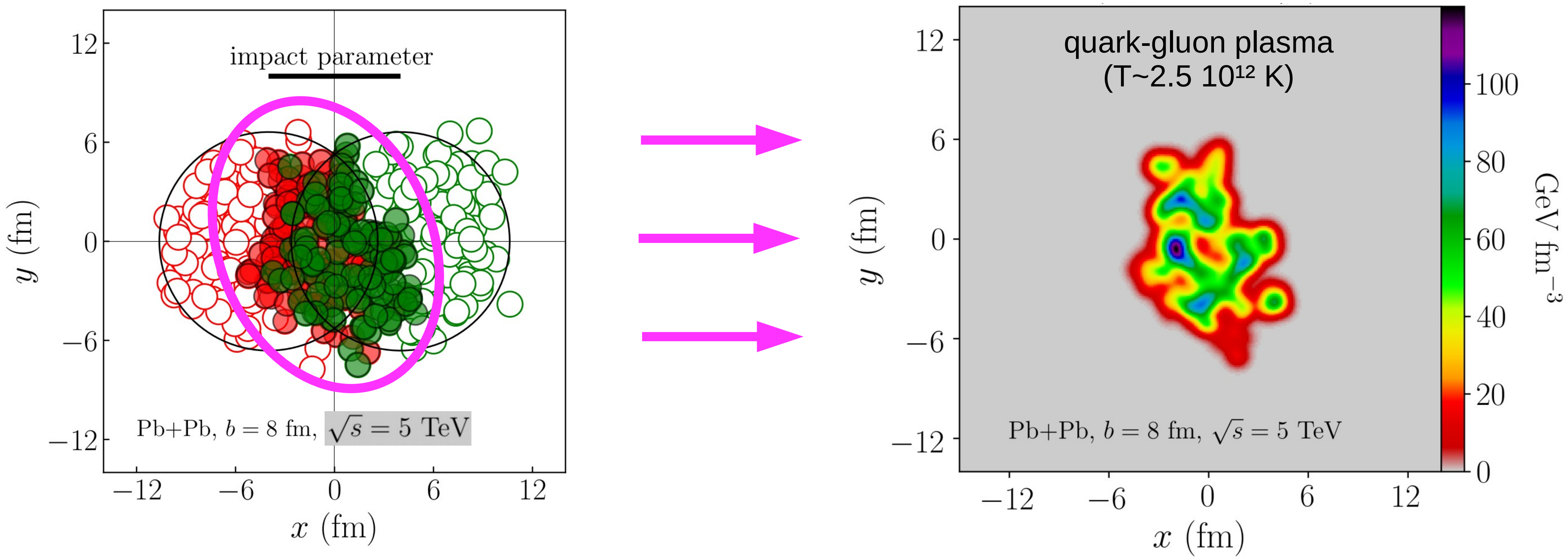
High energy = Nuclei in the lab frame are squeezed in beam direction.



Interaction is instantaneous.

All the relevant dynamics occurs in the plane transverse to the beam.

SNAPSHOT: REPRODUCING THE EARLY UNIVERSE IN THE LAB

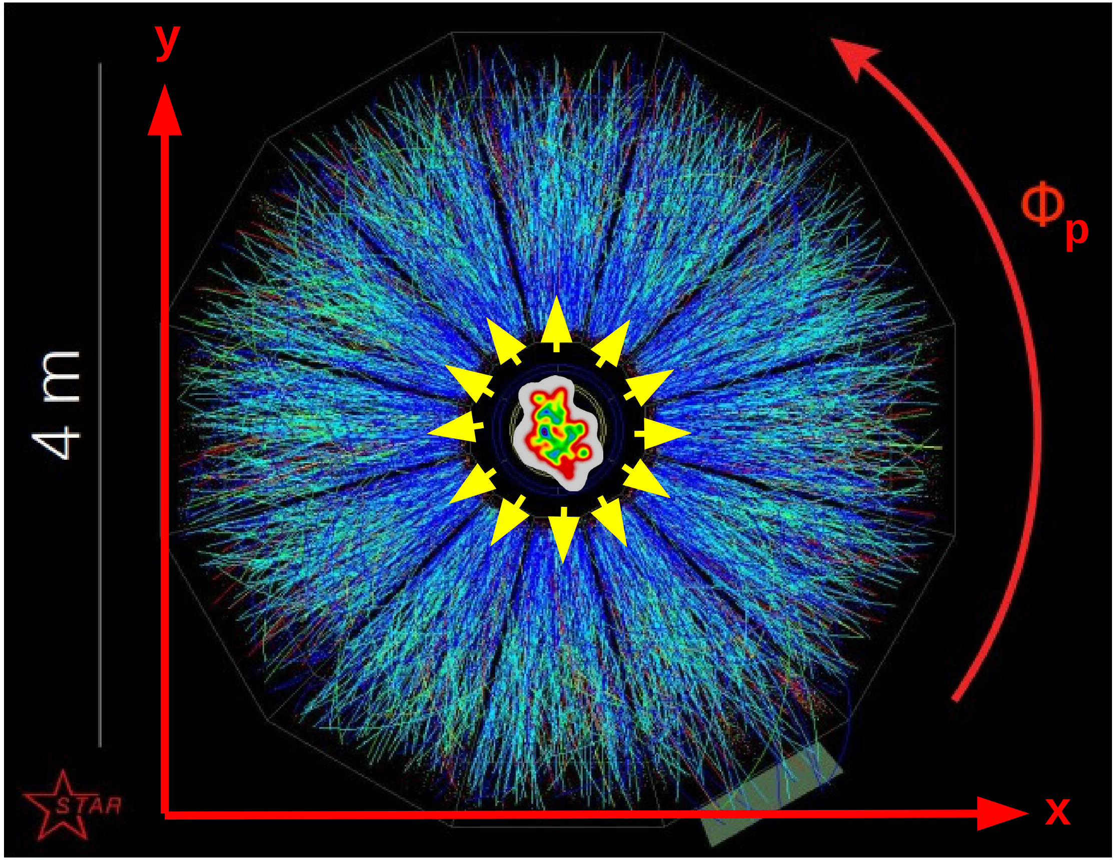


Effective fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ + transport (η/s, ζ/s, ...)

[Romatschke & Romatschke, arXiv:1712.05815]

Main goals: understanding the <u>initial condition</u> and the transport properties.

How do we do that? We only observe particles.



Low-momentum particles follow the hydrodynamic expansion.

$$\frac{d^2N}{dp_T d\phi} = \frac{dN}{2\pi dp_T}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)$$

EXPLOSIVENESS OF THE EXPANSION

ANISOTROPY OF AZIMUTHAL DISTRIBUTION

Vast number of observables.

Key phenomenon: anisotropic flow.

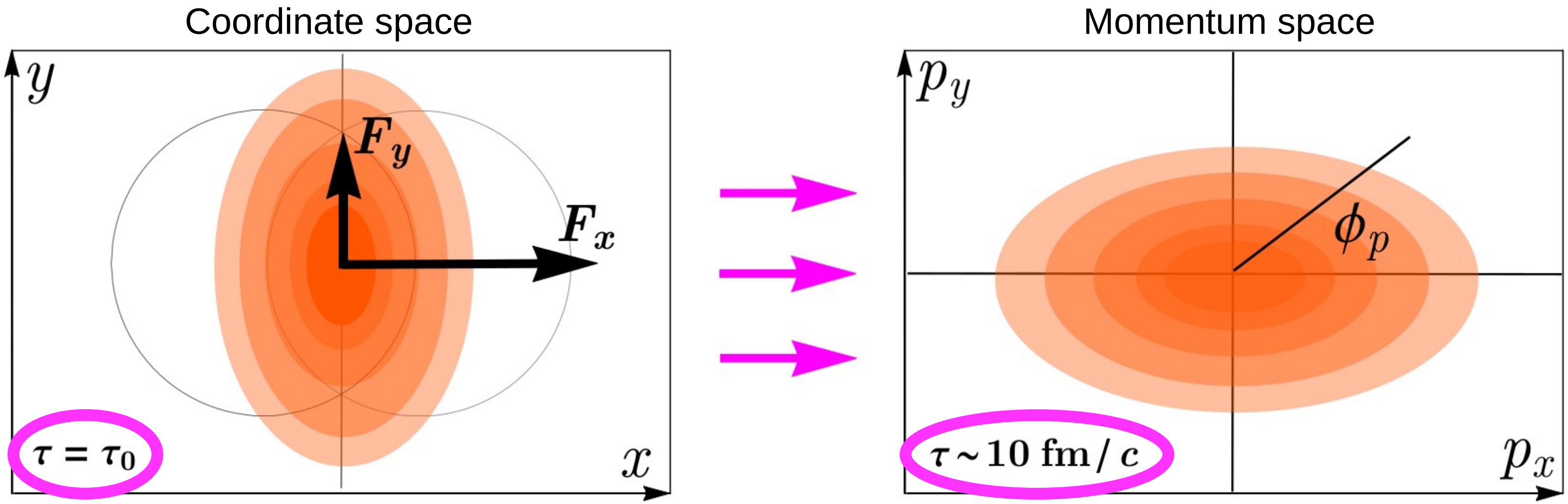
$$F = -\nabla P$$

Shape-flow conversion.

Elliptic flow is the most relevant.

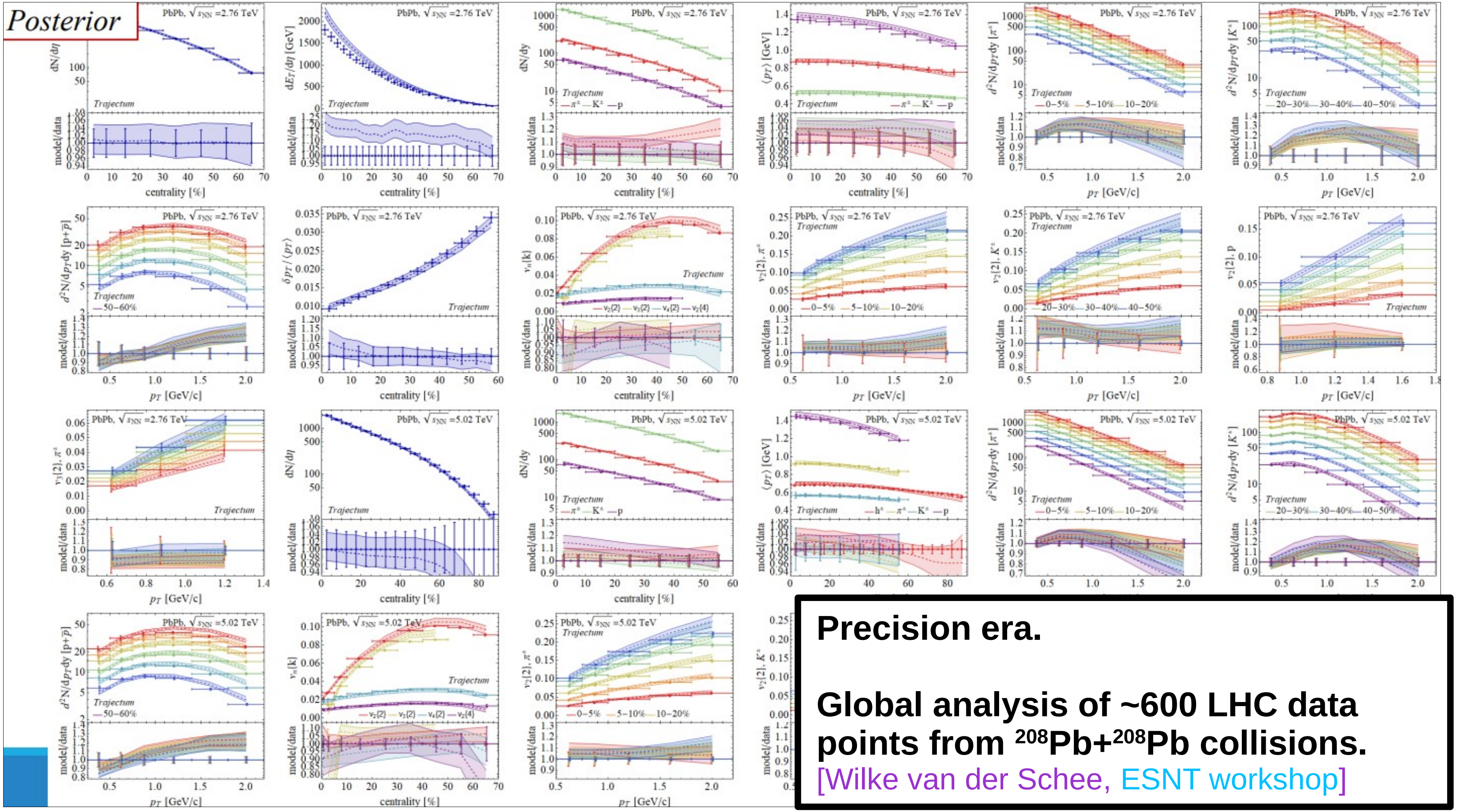
$$V_2 = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-i2\phi_p}$$

[Ollitrault, PRD **46** (1992) 229-245]



Important: it generalizes to all types of shapes.

20 years later: hydrodynamic model constrained via global statistical analyses.



Precision era.

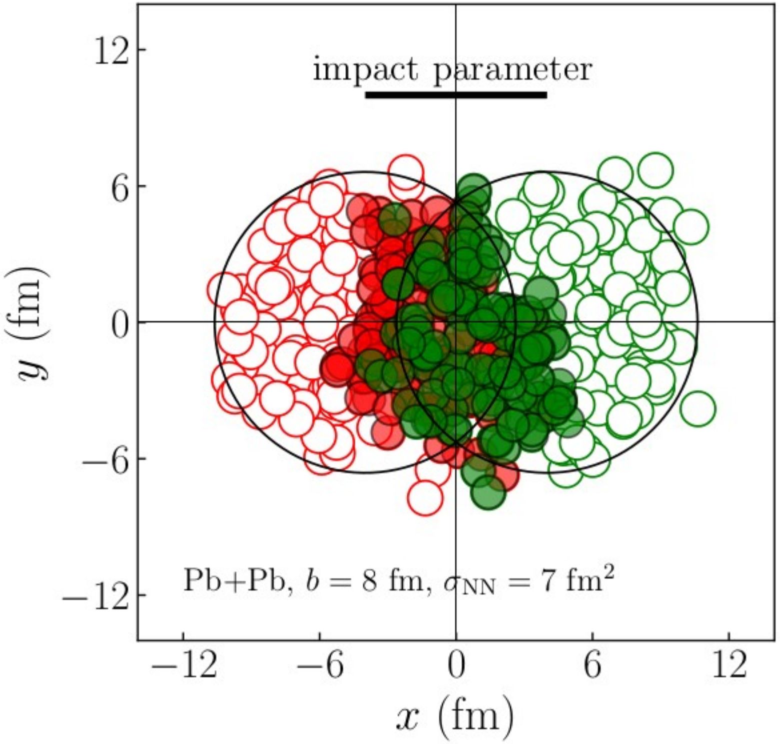
Global analysis of ~600 LHC data points from ^{208}Pb+^{208}Pb collisions.
[Wilke van der Schee, ESNT workshop]

2 – NUCLEAR STRUCTURE INPUT

Formation of QGP starts with nuclear structure.

“Glauber Monte Carlo” approach.

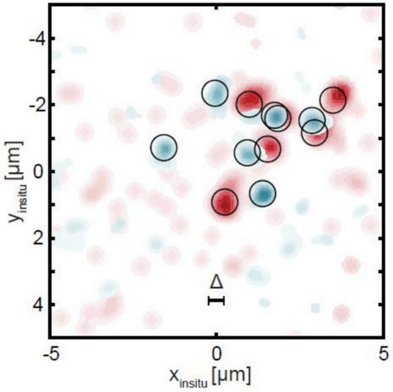
[Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57** (2007) 205-243]



Independent sampling in common density (mean field) is appropriate.

$$V(r_i) = -\frac{V_0}{1+\exp\left(\frac{r_i - R}{a}\right)}$$

“quantum measurement” of the nucleon positions.

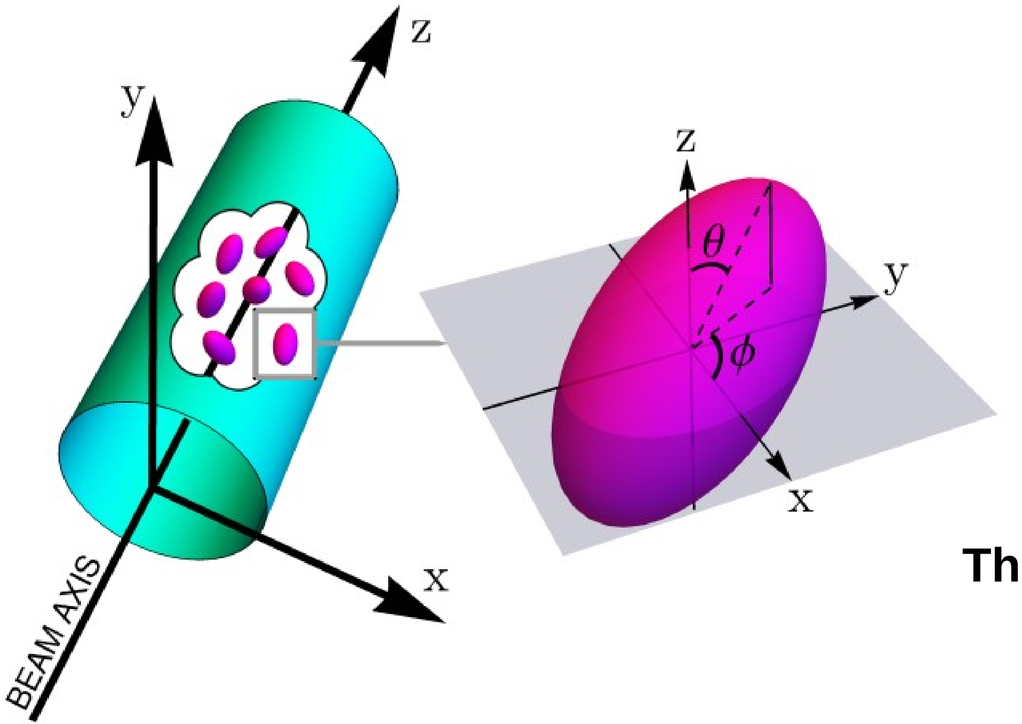


[from Sandra Brandstetter (Heidelberg),
Collapsed wave function of a system of 10 ^{6}Li atoms]

Heavy-ion collisions require *a priori* knowledge of A-body correlation functions, e.g.,

$$\rho_k^{\mathrm{JMNZ}}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4) \equiv \langle \Psi_k^{\mathrm{JMNZ}} | c^\dagger(\vec{r}_1) c^\dagger(\vec{r}_2) c(\vec{r}_3) c(\vec{r}_4) | \Psi_k^{\mathrm{JMNZ}} \rangle$$

Low-energy nuclear physics: Spatial correlations encapsulated in "intrinsic shapes".

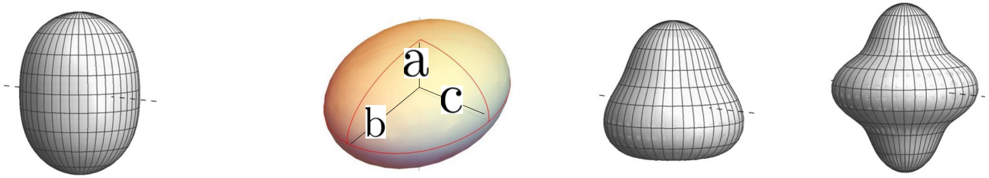


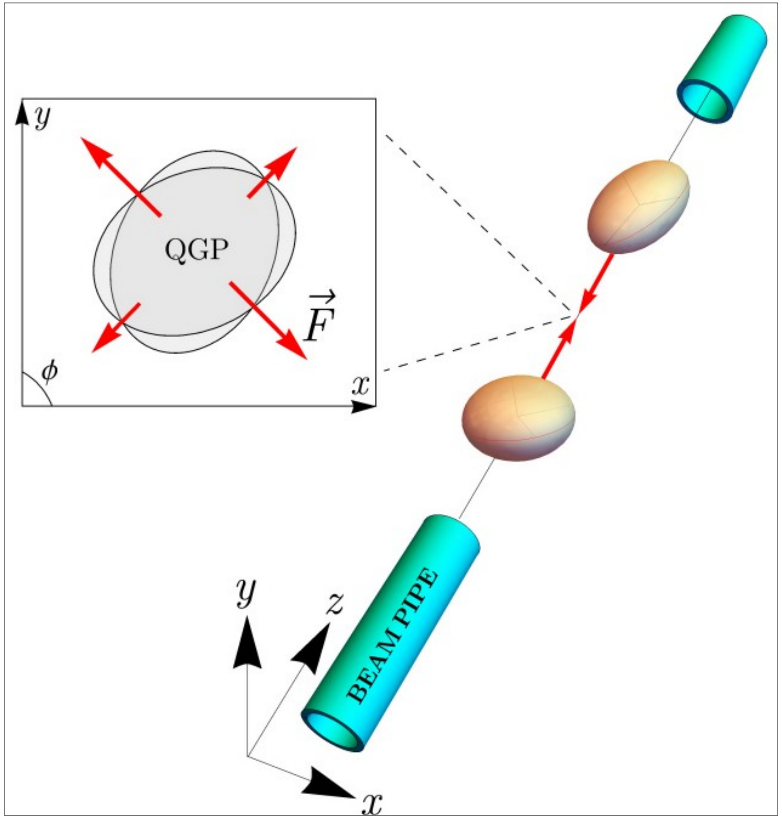
The nucleus as a deformed bag of nucleons with a random orientation.

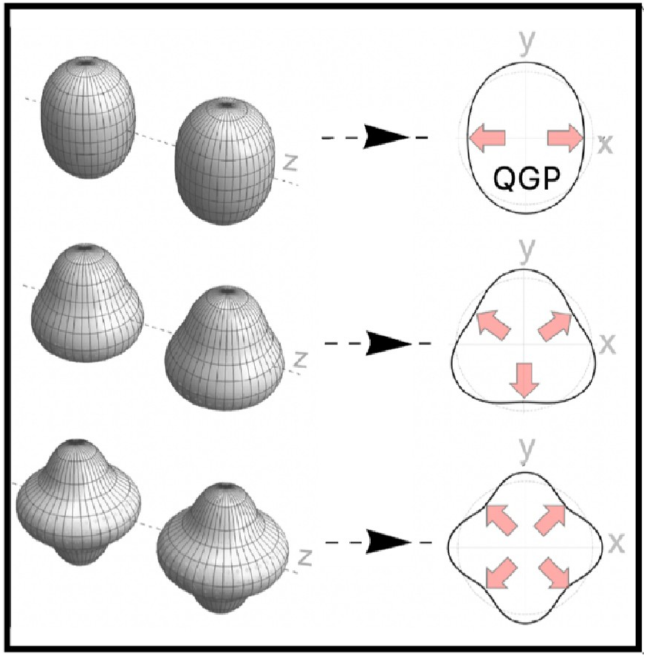
The interaction selects one such orientation.

Generalize the Woods-Saxon profile to include intrinsic deformations:

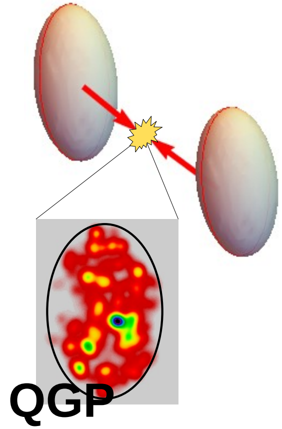
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \ , \quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\Big(\cos\gamma Y_{20}(\Theta)+\sin\underline{\gamma}Y_{22}(\Theta,\Phi)\Big)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$



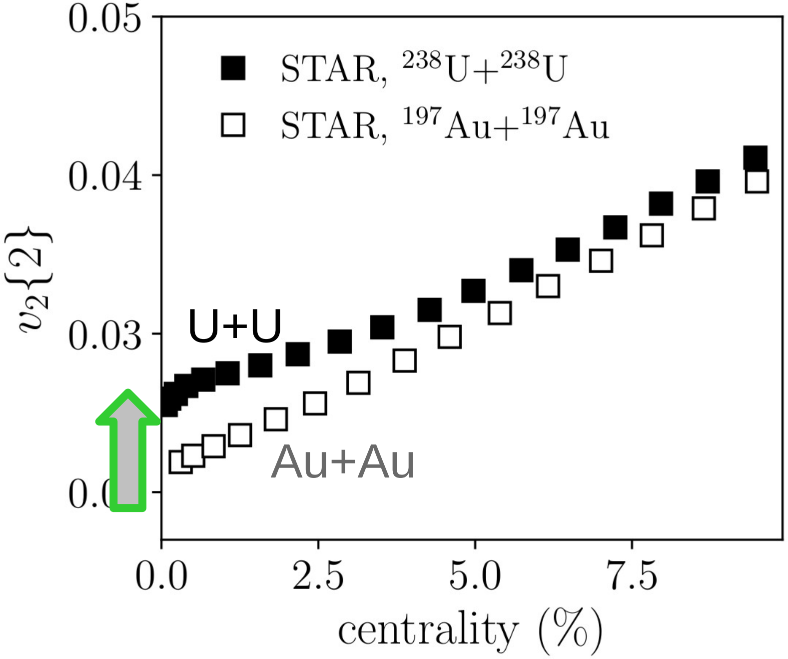




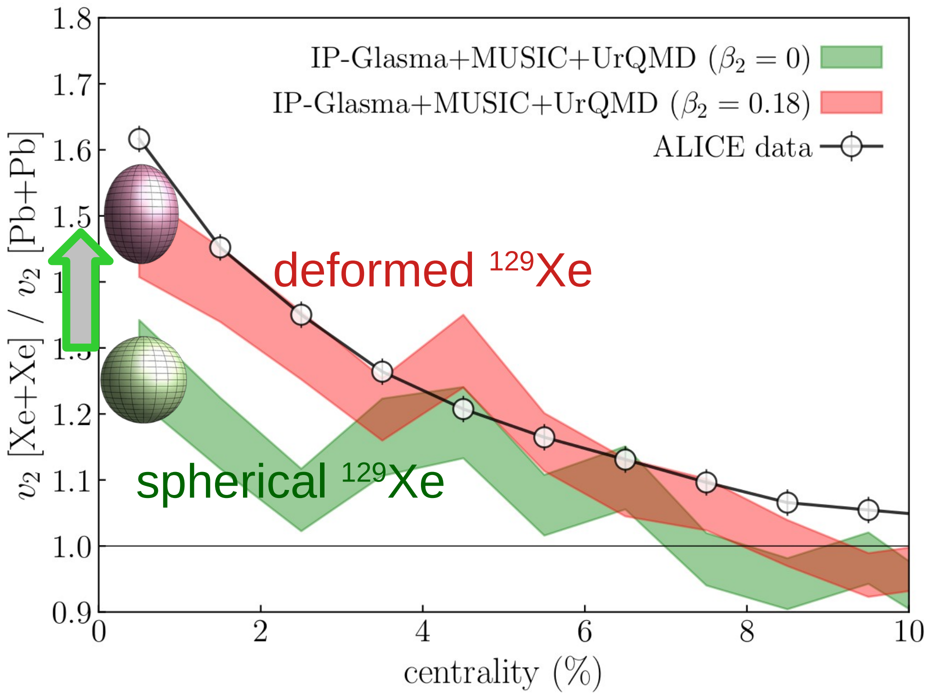
Simple signatures: Enhanced elliptic flow with ^{129}Xe and ^{238}U ions.



Shape-enabled elliptical geometry for the QGP.



[STAR Collaboration, PRL **115** (2015) 22, 222301]



[ALICE Collaboration, PLB **784** (2018) 82-95]

3 – MILESTONES FROM THE PAST TWO YEARS

(2021 – present)

Solid relations between high-energy observables and deformations.

v_n = azimuthal anisotropy of particle distribution
$[p_t]$ = average particle momentum

[Jiangyong Jia, PRC **105** (2022) 1, 014905
PRC **105** (2022) 4, 044905]

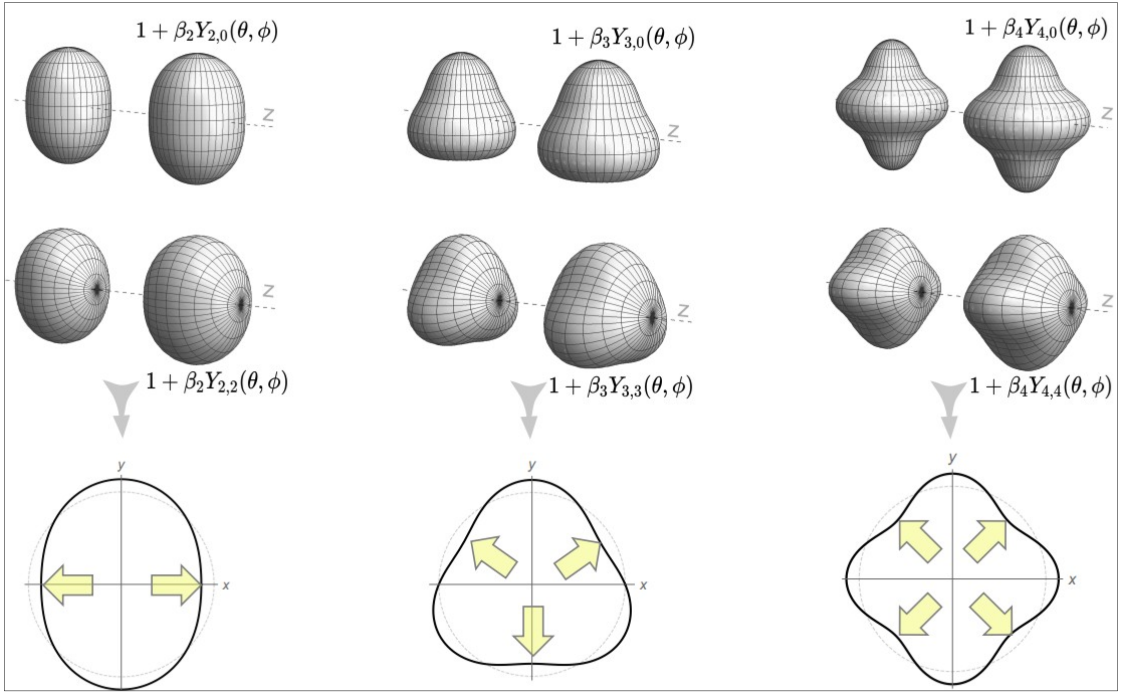
$$\langle v_n^2 \rangle = a_0 + a_1 \beta_n^2$$

$$\langle ([p_t] - \langle [p_t] \rangle)^2 \rangle = b_0 + b_1 \beta_2^2$$

$$\langle v_n^2 ([p_t] - \langle [p_t] \rangle) \rangle = c_0 - c_1 \beta_2^3 \cos(3\gamma)$$

$$\langle ([p_t] - \langle [p_t] \rangle)^3 \rangle = d_0 + d_1 \beta_2^3 \cos(3\gamma)$$

… … …



Well-defined methods.

Mismatch between hydrodynamic simulations and U+U data.

The β_2=0.28 measured from B(E2) has been used for ^{238}U nuclei.

[Giacalone *et al.*, PRL **127** (2021) 24, 242301]

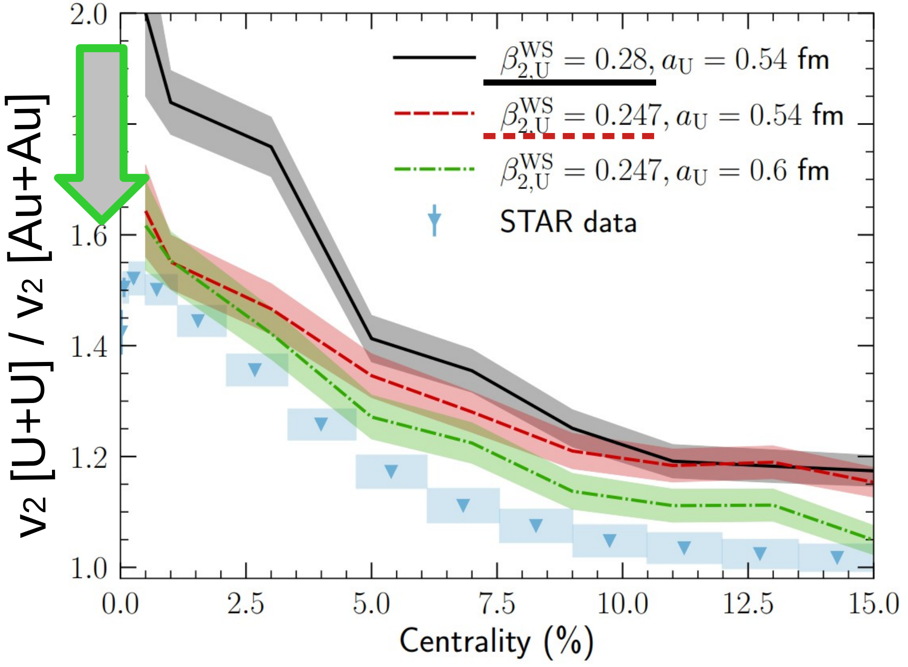
Surface vs. Volume deformation.

volume ~0.28

$$\beta_{20} = \frac{R_d^2}{R_0^2}\left[\beta_{20}^{\mathrm{WS}} + \frac{2}{7}\sqrt{\frac{5}{\pi}}(\beta_{20}^{\mathrm{WS}})^2 + \frac{12}{7\sqrt{\pi}}\beta_{20}^{\mathrm{WS}}\beta_{40}^{\mathrm{WS}}\right]$$

surface ~0.25

[W. Ryssens *et al.*, PRL **130** (2023) 21, 212302]



Consistent implementation of an intrinsic one-body density solves the problem.

Signature of the hexadecapole deformation of ^{238}U in high-energy experiments.

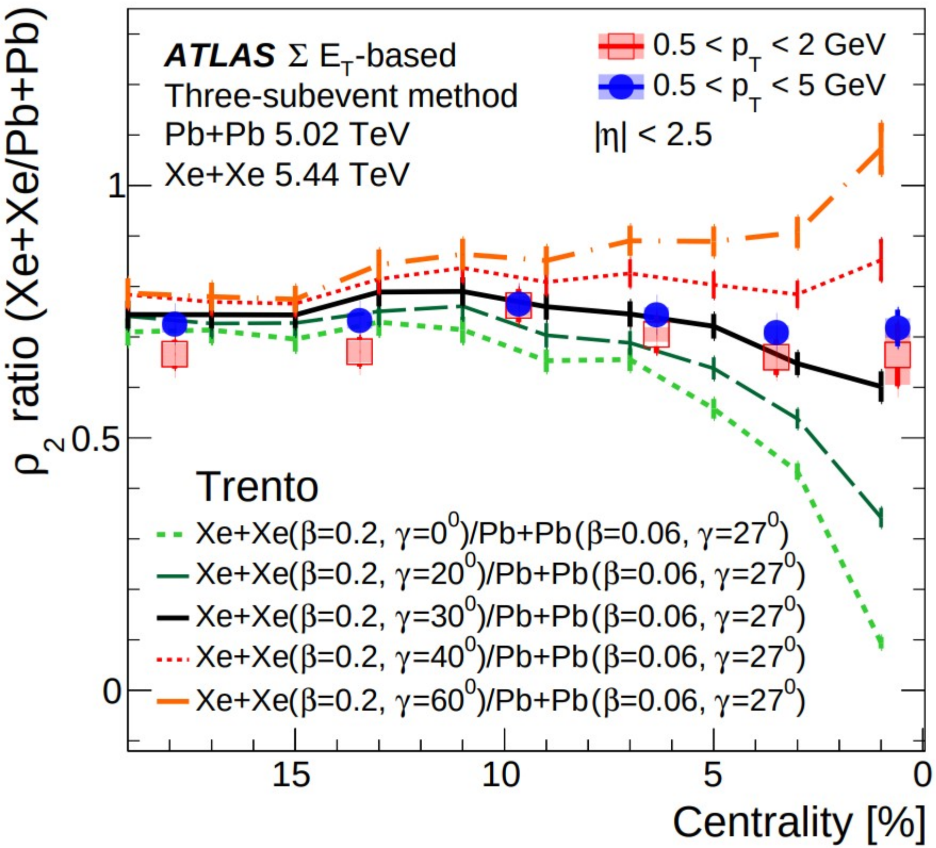
Triaxiality: ^{129}Xe predicted to be triaxial in density-functional theory.

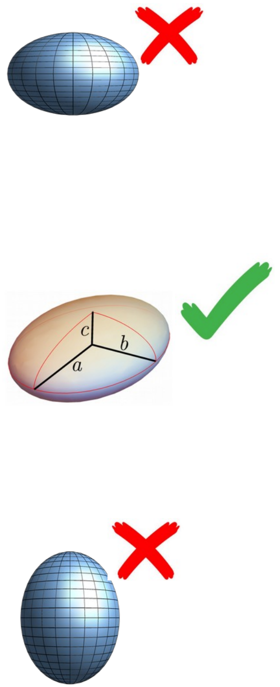
Triaxial nucleus explains LHC data on Xe+Xe collisions.

$$\rho_2 \propto -\cos(3\gamma)\beta_2^3$$

[B. Bally *et al.*, PRL **128** (2022) 8, 082301]

[ATLAS collaboration, PRC **107** (2023) 5, 054910]





For β2 >≈ 0.1, very strong sensitivity to the triaxiality parameter!

Evidence of octupole deformation.

2021 Breakthrough: data from ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr collisions at RHIC.

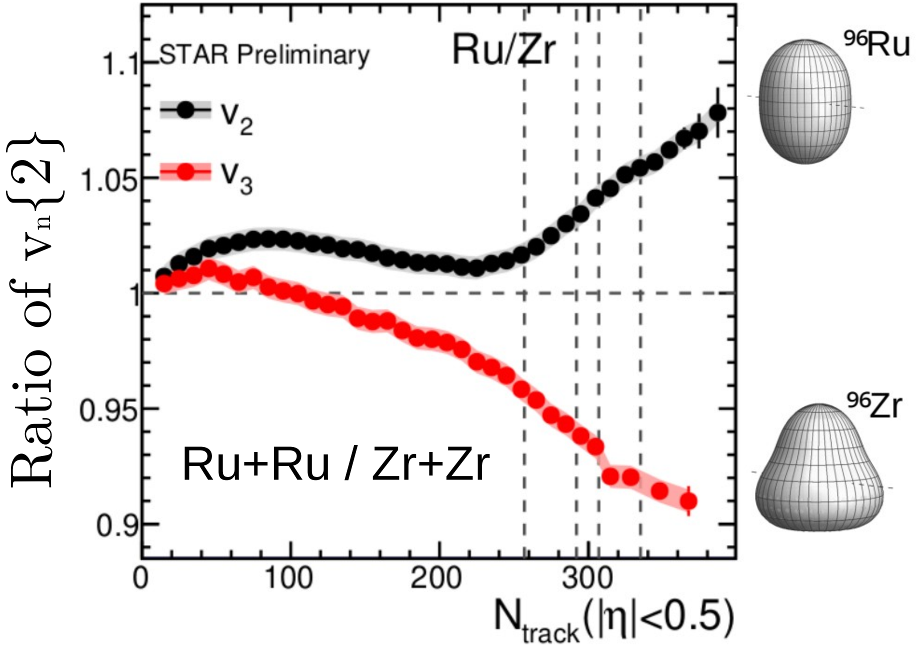
[STAR collaboration, PRC **105** (2022) 1, 014901]

What we see:

– ^{96}Ru has larger β_2 than ^{96}Zr. In line with experiments.

– ^{96}Zr has much bigger octupole deformation.
Is this understood?

[Chunjian Zhang, J. Jia, PRL **128** (2022) 2, 022301]



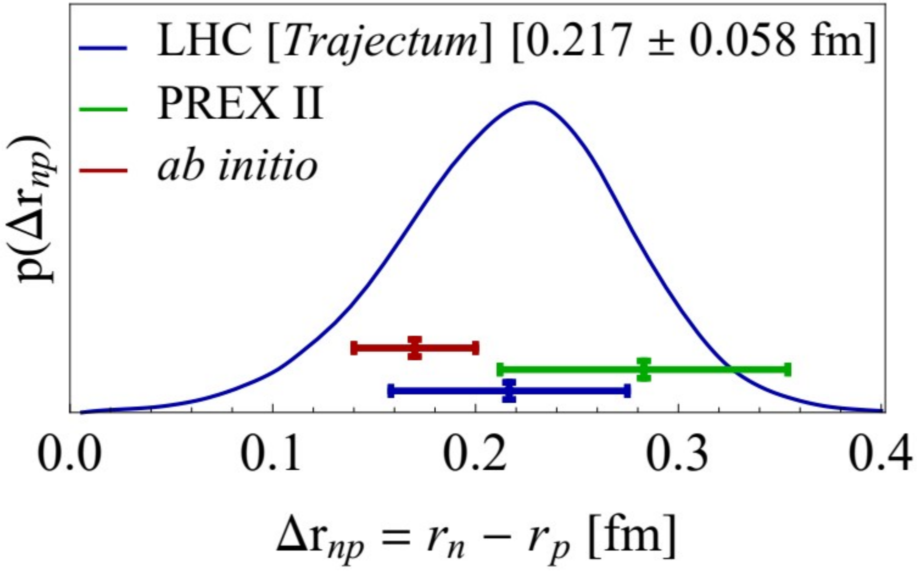
Hints from low lying 3⁻ state in ^{96}Zr in experiments.

[Iskra *et al.*, PLB **788** (2019) 396-400]

Challenge for nuclear structure theory.

Extraction of the neutron skin of ^{208}Pb from a global Bayesian analysis of ^{208}Pb+^{208}Pb data.

[G. Giacalone, G. Nijs, W. van der Schee, arXiv:2305.00015]



Slope parameter of EOS:

$$L = 79 \pm 39\,\mathrm{MeV}$$

PREX II	$0.278 \pm 0.078\ (\mathrm{exp.}) \pm 0.012\ (\mathrm{theo.})\ \mathrm{fm}$
LHC	$0.217 \pm 0.058(\mathrm{theo.})\ \mathrm{fm}$

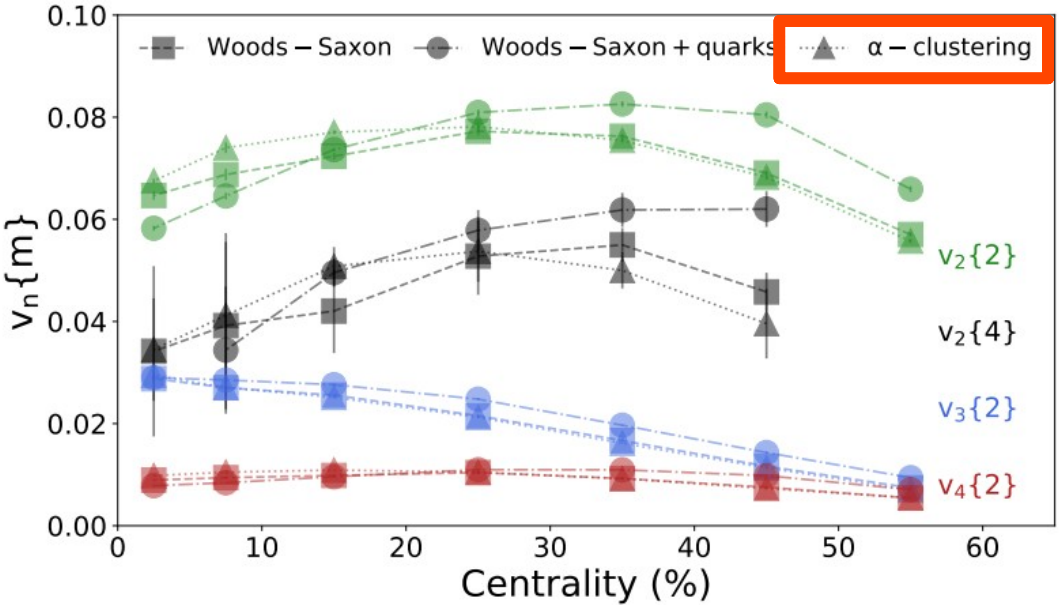
[PREX Collaboration, PRL **126** (2021) 17, 172502]

In future, uncertainty from both sides will go down. Test compatibility.

Contact with *ab initio* community.

Implementation of the results of Nuclear Lattice Effective Field Theory simulations.

[Summerfield *et al.*, PRC **104** (2021) 4, L041901]



O - O $\sqrt{s_{NN}} = 6.5$ TeV

Collisions performed @RHIC in 2021.

Will be performed @LHC in 2024.

State-of-the-art predictions for future collisions of light ion species.

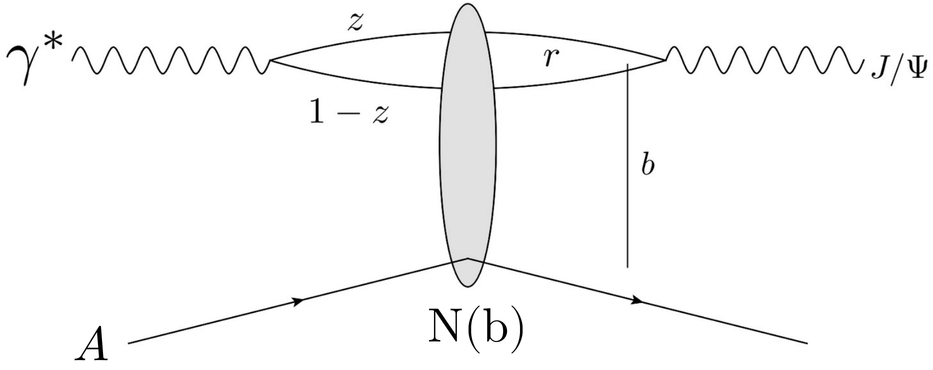
Diffractive photo-production of vector mesons.

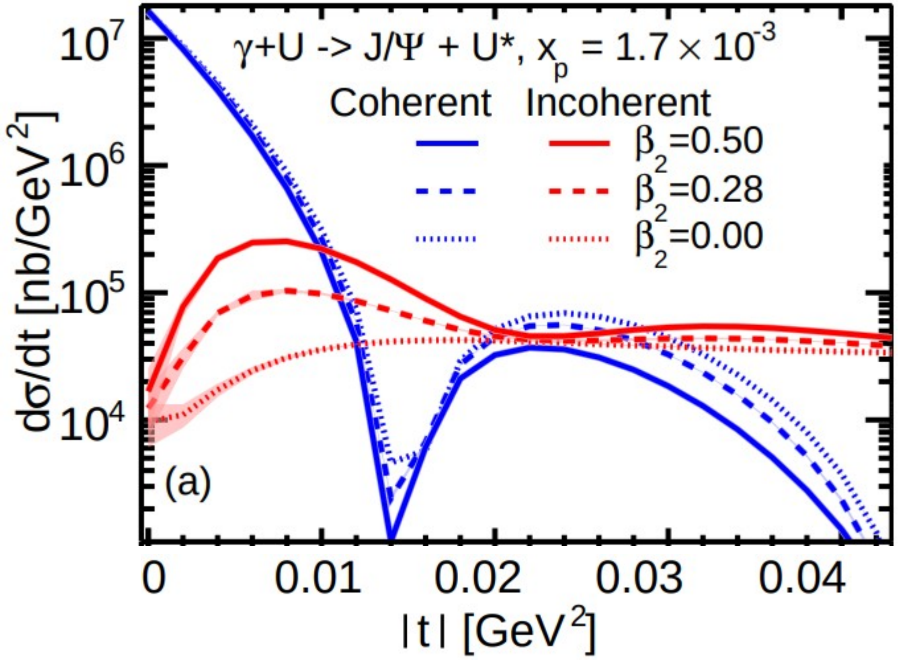
Process probes the two-body density of the ground-state of the nuclear target.

[Caldwell, Kowalski, PRC **81** (2010) 025203]
[Blaizot, Traini, arXiv:2209.15545]

First prediction for a deformed nuclear target.

[H. Mäntysaari et al., arXiv:2303.04866]





Studies of correlations in nuclei at the future Electron Ion Collider.

4 – PROSPECTS

PROSPECTS: THEORY?

@LOW ENERGY:

Improving understanding of dynamical correlations in “difficult” nuclei!

A relevant case: large deformation of ^{96}Zr emerge from symmetry restoration.

[from study of ^{96}Zr by Rong et al., PLB **840** (2023) 137896]

A more solid conclusion should be made based on the result of calculation for the states within the whole $(\beta_{20}, \beta_{22}, \beta_{30}, \beta_{32})$ deformation space, which is too expensive to be carried out in this work.

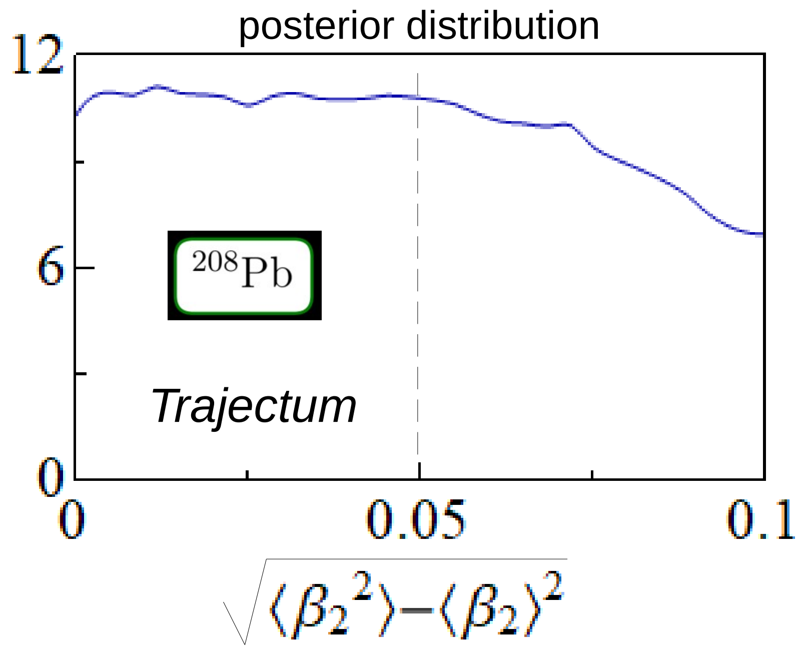
→ **this is what we need!**

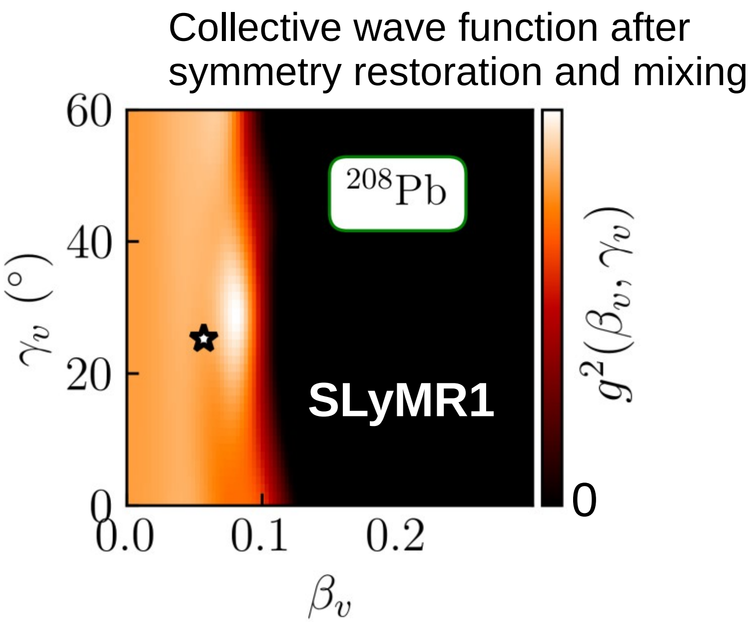
Current energy-density functional calculations are not comprehensive enough.

@HIGH ENERGY: intrinsic deformed shape from global analysis of collider data.

First attempt with ^{208}Pb (deformation as a shape fluctuation).

Shapes 'equiprobable' up to β_2~0.05. Sort of in line with density-functional results.



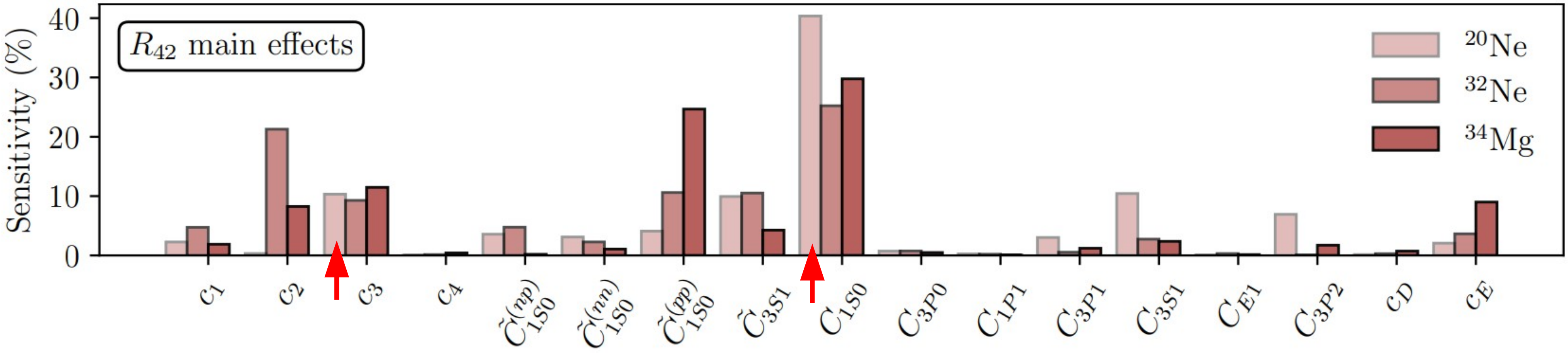


In future, extraction of deformations of ^{96}Ru, ^{96}Zr, ^{129}Xe, ^{238}U will be possible.

END GOALS: What drives deformation in chiral EFT?

Measure of rigid-rotor-like behavior: $R_{42} \equiv E(4^+)/E(2^+)$

Δ-full chiral EFT with 17 low-energy constants. **Global sensitivity analysis.**



A global sensitivity analysis shows that the subleading singlet S-wave contact and a pion-nucleon coupling strongly impact deformation in chiral EFT.

[Ekström *et al.*, arXiv:2305.06955]

END GOALS: Repeat the analysis with high-energy observables?

[Giacalone, arXiv:2305.19843]

$$\left\langle \frac{\sum_{i\neq j} e^{in(\phi_i-\phi_j)}}{N_{\rm ch,ev}(N_{\rm ch,ev}-1)} \right\rangle_{\rm ev} \propto \frac{\int_{\xi_i,\xi_j,\xi_k,\xi_\ell} P_{2\perp}(\xi_i,\xi_j)P_{2\perp}(\xi_k,\xi_\ell) f_2(\xi_i,\xi_j,\xi_k,\xi_\ell)}{\left(\int_{\xi_i,\xi_j} P_{1\perp}(\xi_i)P_{1\perp}(\xi_j) f_1(\xi_i,\xi_j)\right)^2}$$

high-energy physics

measured particle correlations

nuclear N-body densities

Can we mass-produce via emulators the 1- and 2-body densities of nuclei?

High-energy observables may show unique sensitivities to features of the interaction.

Complementarity of nuclear experiments?

PROSPECTS:
EXPERIMENT?

Imaging nuclear structure and quark-gluon plasma at the Large Hadron Collider

Not scheduled

20m

NuPECC LRP2024 Community input

Description

It has been established recently that nuclear collision experiments performed in high-energy collider machines, such as the CERN Large Hadron Collider (LHC), provide a novel tool to observe signatures of the shape and the radial structure of atomic nuclei. By taking snapshots of the state of the colliding ions at the interaction point, such experiments open an access route to a range of phenomena shaped by the collective behavior of nucleons that emerge from the strong nuclear force, such as nuclear deformations and neutron skins. The European nuclear community should explore the potential of a program of high-energy collisions across the Segrè chart to be pursued beyond LHC Run 3 to exploit the synergy between two areas of nuclear science. This will permit us, on the one hand, to advance our knowledge of the conditions that set the stage for the formation of quark-gluon plasma (QGP) in heavy-ion collisions and better constrain key physical parameters associated with the Hubble-like expansion of this medium. On the other hand, full exploitation of the LHC as an imaging tool will advance our understanding of strongly-correlated nuclear systems via probes and techniques complementary to those utilized in low-energy applications. Such studies will ultimately yield unique insight into the behavior of quantum chromodynamics (QCD) across systems and energy scales.

Primary author

Giuliano Giacalone (Heidelberg Universit...

Co-author

Prof. You Zhou (Niels Bohr Institute)

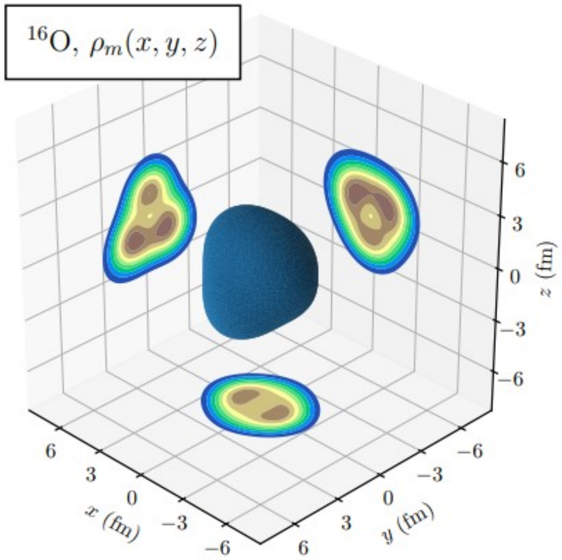
https://indico.ph.tum.de/event/7050/contributions/6321/

A case with oxygen and neon isotopes (LHC Run 3-4?)

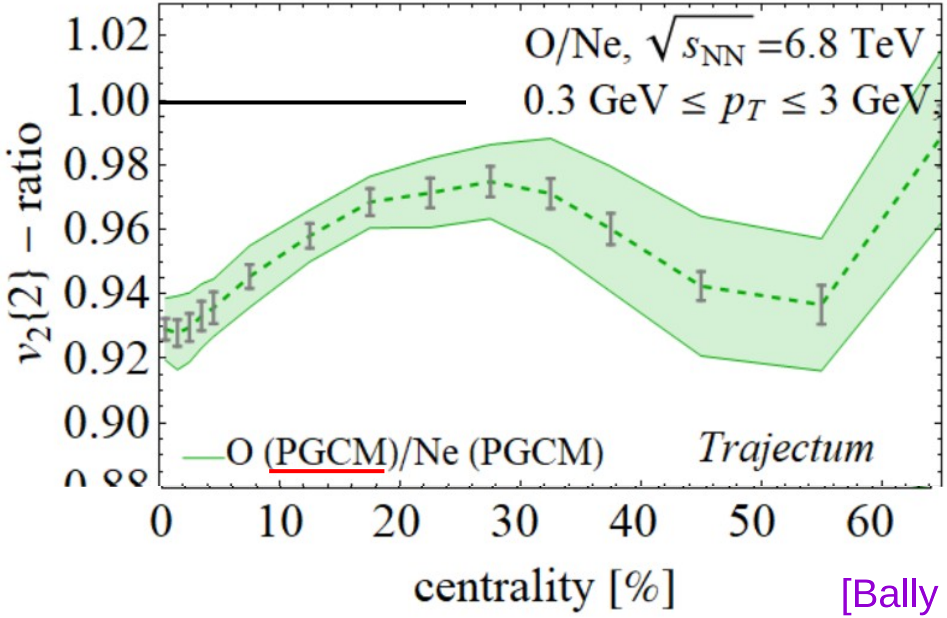
QCD matter formed in "small systems" behaves like a near-ideal liquid?

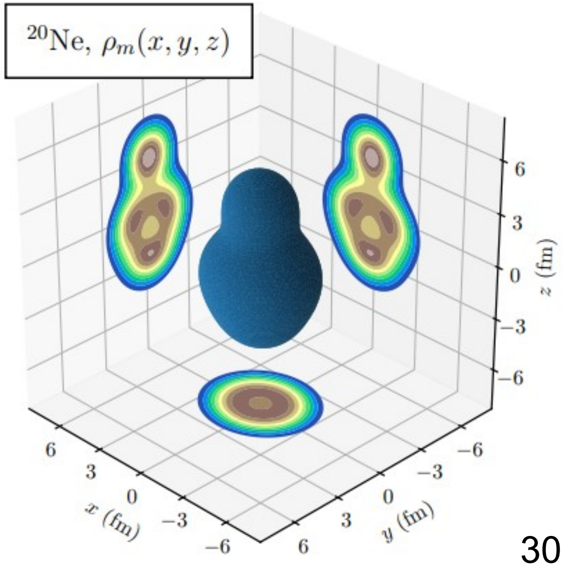
Exploiting cutting-edge *ab initio* results.

[*ab initio* PGCM, Frosini et al., CEA Saclay]



Ideal scenario: complement with a short run of ^{20}Ne ions.





[Bally et al. in preparation]

Collisions of additional species @ LHC Run 5 and Run 6?

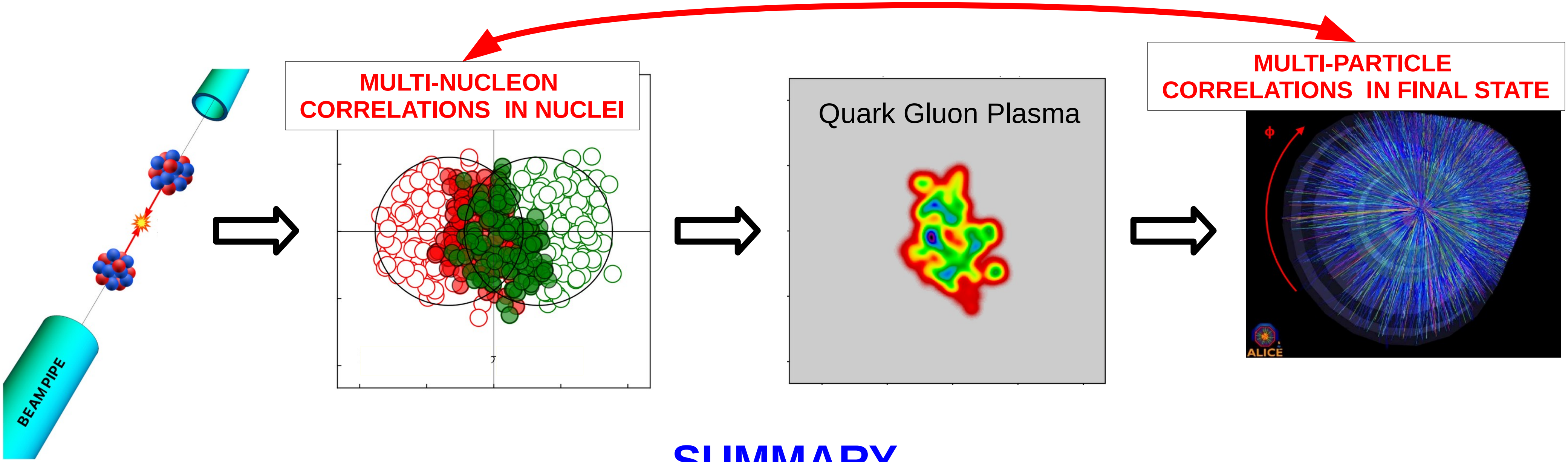
[from Alexander Kalweit, ESNT workshop] [https://indico.cern.ch/event/1078695/]

Nucleon-nucleon luminosity: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$

optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

Maximizing impact. Case studies to be developed together.

Synergy with the Electron Ion Collider?



SUMMARY

- **Very precise nuclear structure knowledge required for simulations of collisions of nuclei at high energy.**
- **At the same time, precise information about correlations in nuclei is accessible via high-energy collisions.**
- **Complementary means to understand QCD across energies?**
- **Looking forward to future progress and collaborations.**

THANK YOU